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S. Fourmaux, Sébastien Corde, K. Ta Phuoc, P. M. Leguay, S. Payeur, et al.. Demonstration of the synchrotron-type spectrum of laser-produced Betatron radiation. *New Journal of Physics*, 2011, 13, pp.033017. 10.1088/1367-2630/13/3/033017 . hal-01164324

**HAL Id: hal-01164324**

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Submitted on 16 Jul 2015

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## Demonstration of the synchrotron-type spectrum of laser-produced Betatron radiation

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*New Journal of Physics* **13** (2011) 033017 (8pp)

Received 13 September 2010

Published 9 March 2011

Online at <http://www.njp.org/>

doi:10.1088/1367-2630/13/3/033017

**Abstract.** Betatron x-ray radiation in laser–plasma accelerators is produced when electrons are accelerated and wiggled in the laser-wakefield cavity. This femtosecond source, producing intense x-ray beams in the multi-kiloelectronvolt (keV) range, has been observed at different interaction regimes using a high-power laser from 10 to 100 TW. However, none of the spectral measurements carried out were at sufficient resolution, bandwidth and signal-to-noise ratio to precisely determine the shape of spectra with a single laser shot in order to avoid shot-to-shot fluctuations. In this paper, the Betatron radiation produced using a 80 TW laser is characterized by using a single photon counting method. We measure in a single shot spectra from 8 to 21 keV with a resolution better than 350 eV. The results obtained are in excellent agreement with theoretical predictions and demonstrate the synchrotron-type nature of this radiation mechanism. The critical energy is found to be  $E_c = 5.6 \pm 1$  keV for our experimental conditions. In addition, the features of the source at this energy range open up novel opportunities for applications in time-resolved x-ray science.

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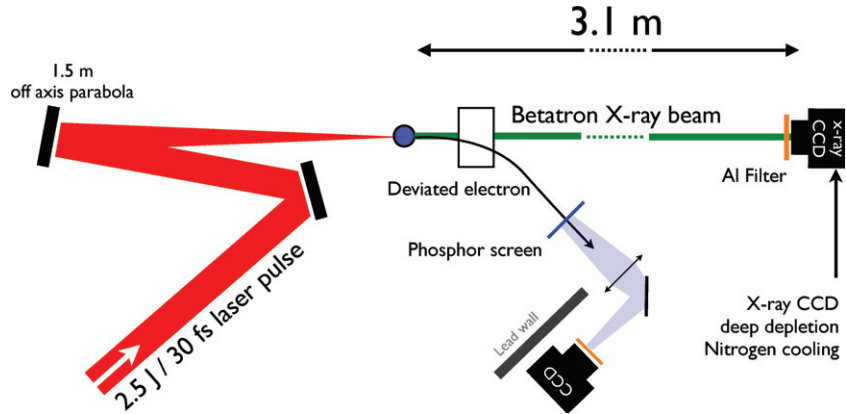
A femtosecond x-ray beam, called Betatron, can be produced by focusing an intense femtosecond laser pulse at relativistic intensities, of the order of  $10^{18}$ – $10^{19}$  W cm $^{-2}$ , onto a gas jet target. Interacting with the quasi-instantaneously created under-dense plasma, the laser pulse excites a wakefield in which electrons can be trapped and accelerated to high energies in short distances [1]–[5]. These electrons perform Betatron oscillations across the propagation axis, and emit x-ray photons [6]–[10] (radiation from accelerating charged particles). The Betatron radiation consists of a broadband x-ray beam, collimated within tens of mrad, with a femtosecond duration [11].

Over the past few years, several experiments have been dedicated, at different laser facilities, to the characterization of Betatron radiation. Even if the origin of the radiation was clearly identified, its spectrum has never been precisely determined. This information is, however, crucial to improve our knowledge of the physical mechanisms driving the source, identify the electrons participating in the emission and determine the most appropriate routes for its development. In addition, for any potential application, the precise shape of the spectrum must be known.

So far, spectra estimations were done either based on the measurement of the transmission through an array of filters or by using the diffraction from crystals. The use of filters is the most elementary method and allows a single shot measurement. The results obtained using this method are generally fitted to the synchrotron distribution theoretically predicted [12]–[15]. However, this relies on the assumption that the spectrum is synchrotron-like and cannot give any deviation from such distribution, or details of the structure of the spectrum. When the Bragg diffraction from a crystal is used, the resolution is important but the characterization range is limited to about 1–3 keV [16] and the measurement requires an accumulation over about ten laser shots for each energy point. Consequently, this method is very sensitive to the strong fluctuations of the Betatron spectrum and can only provide a mean spectrum of the source. To overcome the limitations of the preceding methods, photon counting can be a relevant method. For a sufficiently intense source and an appropriate experimental setup, we will show that it can provide a single shot measurement of the source over a large bandwidth. A photon-counting-based measurement of the Betatron source has recently been used in the range 1–9 keV and a continuous spectrum was observed, but its structure was not revealed because it was not deconvoluted by the filter transmission and the charged-coupled device (CCD) response [17, 18].

In this paper, we present single shot photon counting measurements of the Betatron x-ray radiation spectrum in the 8–21 keV energy range with a resolution better than 350 eV. Thanks to this method, the results demonstrate the synchrotron-type nature of the Betatron radiation and its direct correlation with the accelerated electron energy spectrum, which was simultaneously measured. In the experiment presented, the Betatron radiation was produced at the interaction of a 80 TW/30 fs laser pulse with a gas jet target density of the order of  $10^{18}$ – $10^{19}$  cm $^{-3}$ . We will show that the experimental spectrum fits a synchrotron distribution of critical energy  $E_c = 5.6 \pm 1$  keV.

In a laser-plasma accelerator, electrons are both accelerated longitudinally and wiggled transversely by the electromagnetic wakefields. The transverse oscillation is nearly sinusoidal at the Betatron frequency  $\omega_\beta = \omega_p / \sqrt{2\gamma}$  [6, 7], where  $\gamma$  is the relativistic factor of the electron and  $\omega_p = (n_e e^2 / m_e \epsilon_0)^{1/2}$  the plasma frequency, with  $n_e$  the electron density,  $e$  the electron charge and  $m_e$  the electron mass. Due to this oscillatory motion, radiation is emitted with properties depending on the strength parameter  $K = r_\beta k_p \sqrt{\gamma/2}$  ( $r_\beta$  is the Betatron transverse amplitude

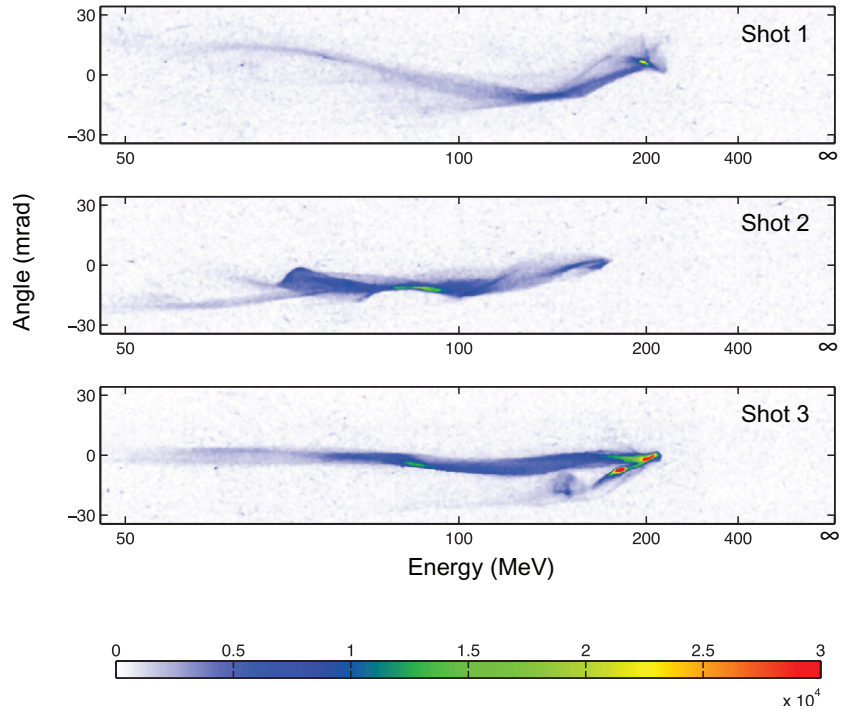


**Figure 1.** Schematic diagram of the experimental setup for electron acceleration and Betatron x-ray generation.

of motion and  $k_p = \omega_p/c$ ), on the Betatron frequency  $\omega_\beta$  and on the electron energy  $\mathcal{E} = \gamma mc^2$ . For  $K \ll 1$ , the on-axis radiation spectrum is nearly monochromatic at the fundamental frequency  $\omega = 2\gamma^2\omega_\beta/(1 + K^2/2)$ . As  $K \rightarrow 1$ , harmonics of the fundamental start to appear in the spectrum, and for  $K \gg 1$ , the spectrum contains many closely spaced harmonics and extends up to a critical frequency  $\omega_c = 3K\gamma^2\omega_\beta/2$ . Experimental data [9, 10], [12]–[14] have shown that Betatron oscillations occur in the wiggler regime,  $K \gg 1$ . In this latter regime, for a single electron with constant parameters  $K$ ,  $\omega_\beta$  and  $\gamma$ , the integrated radiation spectrum is similar to the synchrotron spectrum, which is given by  $dI/d\omega \propto S(x = \omega/\omega_c) = \int_x^\infty K_{5/3}(\xi) d\xi$ , where  $K_{5/3}$  is a modified Bessel function of the second kind. But because electrons are accelerating with changing parameters and because different electrons may have different parameters, a Betatron spectrum is probably more correctly described by a sum of synchrotron distributions [19].

The experiment has been performed at the Advanced Laser Light source (ALLS) facility at INRS-EMT [20], using a titanium-doped sapphire (Ti:sapphire) laser operating at 10 Hz with a central wavelength of 800 nm in chirped-pulse amplification mode. The ALLS laser system delivered 2.5 J of energy on the target with a full-width at half-maximum (FWHM) duration of 30 fs (80 TW) and linear polarization. The experimental setup for electron acceleration and Betatron x-ray generation is presented in figure 1. The laser pulse was focused by an  $f = 1.5$  m off-axis parabolic mirror onto a supersonic helium gas jet. In the focal plane, the FWHM spot size was  $24 \mu\text{m}$  and the encircled energy in this FWHM spot size was 30% of the total energy. This corresponds to an initial laser intensity of  $3 \times 10^{18} \text{ W cm}^{-2}$  and a normalized vector potential amplitude of  $a_0 = eA_0/m_e c = 1.2$ . The gas jet density profile was characterized by interferometry [21]. In this experiment, we used a 3 mm diameter helium gas jet whose density profile has a well-defined 2.1-mm-long electron density plateau of  $n_e = 5.4 \times 10^{18} \text{ cm}^{-3}$ .

The electron beam produced in the interaction was measured with a spectrometer consisting of a permanent dipole magnet (1.1 T over 10 cm) that deflects electrons depending on their energy and a Lanex phosphor screen to convert a fraction of the electron energy into 546 nm light imaged by a CCD camera [22]. Three typical raw electron spectra recorded in the experiment are displayed in figure 2. This shows that electrons are accelerated up to approximately 200 MeV, and that transverse structures are present in the raw spectra (correlation between energy and exit angle), which are reminiscent of the Betatron motion in the laser–plasma accelerator [23].



**Figure 2.** Three typical raw electron spectra (shots 1–3). Horizontal axis, electron energy; vertical axis, exit angle; color scale, number of counts. The latter gives an indication of the beam charge.

X-rays produced by the accelerated electrons were measured using a deep-depletion x-ray CCD (model PI-LCX:1300 cooled with liquid nitrogen), with  $1340 \times 1300$  imaging pixels of size  $20 \mu\text{m} \times 20 \mu\text{m}$ . The x-ray CCD was directly connected and vacuum pumped via the interaction chamber. The quantum efficiency extended well above 20 keV, allowing us to count x-ray photons beyond 10 keV. First, we placed the x-ray CCD close to the x-ray source (distance of 1.2 m) in order to measure the x-ray angular profile. Typical measured angular spreads of the x-ray beams were of the order of 20 mrad (FWHM). Using an array of aluminum filters of different thicknesses (4, 34, 64 and  $124 \mu\text{m}$ ), the measurement of the transmission through each filter can be used to fit for the best synchrotron distribution reproducing the data. Using the synchrotron distribution  $S(\omega/\omega_c)$  defined above, we obtained a best fit for  $E_c = \hbar\omega_c = 5.7 \text{ keV}$ . However, this method is very imprecise and does not allow us to obtain any details of the x-ray spectrum or any deviation from a unique synchrotron distribution.

A precise measurement of the x-ray spectrum can be achieved by photon counting [24, 25]. The CCD camera is composed of  $1340 \times 1300$  pixels, i.e. 1 740 000 independent detectors, and a single photon detected by one of these detectors gives the number of counts (analog to digital converter (ADC) unit), which is proportional to its energy:  $N_c = \alpha \hbar\omega$ , where  $N_c$  is the number of counts and  $\hbar\omega$  the photon energy. For our ADC settings, we obtained  $\alpha = 0.11$  count per eV by calibrating the x-ray CCD using  $K_\alpha$  lines emitted in laser–solid interaction and using the Betatron x-ray beam passing through a Cu filter, which has a sharp cut-off at 8.98 keV. If the number of photons per pixel is small compared to one, piling events (several photons detected on a single pixel) can be neglected and the measurement of the x-ray spectrum becomes possible. A single photon leads to the formation of an electron cloud



in the silicon layer of the CCD chip, which can spread over several neighboring pixels. This phenomenon has to be taken into account in the data analysis. We used a first algorithm able to detect events spreading over a few pixels (multi-pixel event, MPE) and a second algorithm that only takes into account non-spreading events in which the electron cloud is detected on only one pixel (single-pixel event, SPE). For an MPE, the photon energy can be recovered by summing the number of counts over all pixels of the event. However, we found that the MPE algorithm had a lower energy resolution and was more sensitive to piling events than the SPE algorithm. On the other hand, to recover the experimental spectrum from the SPE method, it is necessary to know the probability that a single photon yields a single-pixel event,  $k1(\hbar\omega)$ , which depends on the photon energy  $\hbar\omega$ . This function was obtained from a simulation modeling our CCD response and providing  $k1(\hbar\omega)$  [25]. The experimental spectrum is then recovered by

$$\frac{dN_X}{d(\hbar\omega)} = \frac{a}{k1(\hbar\omega)QE(\hbar\omega)T(\hbar\omega)} \frac{dN_c}{d(\hbar\omega)} \times \frac{dN_{SPE}}{dN_c}, \quad (1)$$

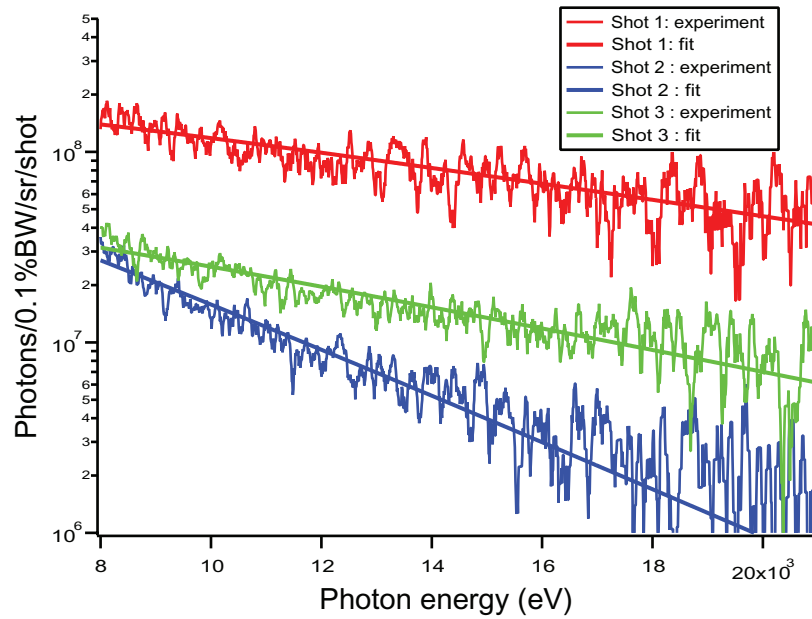
where  $dN_{SPE}/dN_c$  is the number of single-pixel events for each number of counts obtained from the SPE algorithm,  $dN_c/d(\hbar\omega) = \alpha = 0.11 \text{ count eV}^{-1}$ ,  $QE(\hbar\omega)$  is the CCD quantum efficiency,  $T(\hbar\omega)$  is the transmission of the filters placed before the CCD,  $a$  is a numerical factor and  $dN_X/d(\hbar\omega)$  is the number of photons per unit energy (in  $\text{eV}^{-1}$ ). The numerical factor  $a$  comes from the fact that many SPE photons are not analyzed by the algorithm because they are superposed or situated next to other photons. This factor  $a$  is obtained by requiring that the spectrum  $dN_X/d(\hbar\omega)$  leads to the correct total number of counts in the CCD image. It should be noted that contrary to [17], the studied energy range does not contain any edge or line emission, making the analysis easier. In the present work, the energy range is limited to low energy by the Al filter thickness used to reduce the number of photons on the CCD camera. The energy range could be extended to lower energies by setting the detector farther away.

In order to operate in photon counting mode, we placed the x-ray CCD at a distance of 3.1 m from the source, as shown in figure 1, and we attenuated the signal using an Al filter with a thickness of  $274 \mu\text{m}$ . We collected photons in a solid angle of  $\Omega = 7.3 \times 10^{-5} \text{ sr}$  around the propagation axis.

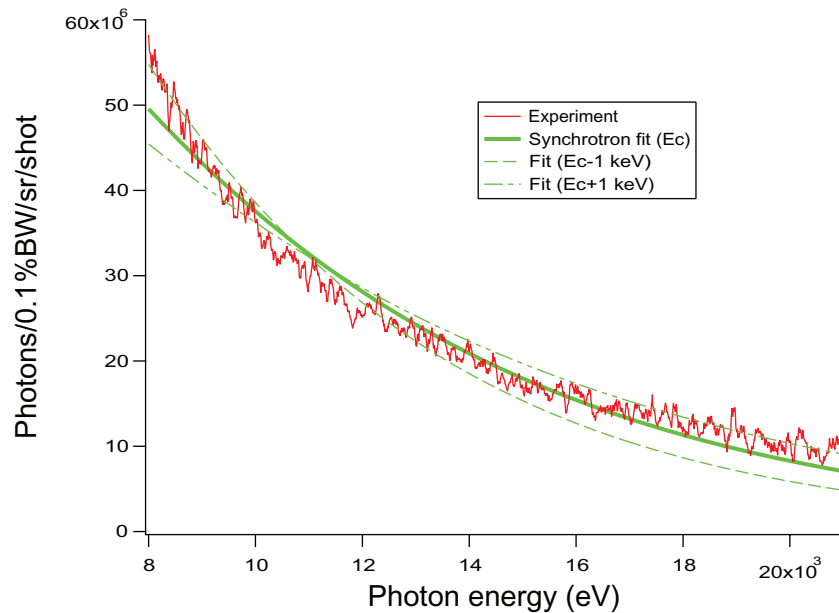
Figure 3 displays the measured experimental spectra of Betatron x-rays by photon counting corresponding to each laser shot whose electron energy spectra have already been shown in figure 2. The estimated energy resolution is better than 350 eV. A fit of the experimental measurements by a synchrotron distribution (of the type  $S(\omega/\omega_c)$  as defined above) is also shown for each laser shot. The best fit was, respectively, obtained with a synchrotron distribution of critical energy  $E_c = \hbar\omega_c = 8.5 \text{ keV}$ ,  $E_c = \hbar\omega_c = 3.2 \text{ keV}$  and  $E_c = \hbar\omega_c = 6.6 \text{ keV}$  (shots 1–3).

Since both the electron and x-ray photon spectra are simultaneously obtained in a single laser shot, they can be correlated. If we consider shot 1 shown both in figures 2 and 3, we observe important Betatron oscillations combined with a high electron charge at 200 MeV. This is well correlated with a high critical energy ( $E_c = \hbar\omega_c = 8.5 \text{ keV}$ ) and a large number of photons (more than  $10^8$  photons/0.1% bandwidth/sr/shot). For shot 2, the maximum electron charge is well below 200 MeV and the Betatron oscillations are small compared with shot 1. This is well correlated with the small critical energy  $E_c = \hbar\omega_c = 3.2 \text{ keV}$ .

Figure 4 displays the measured experimental spectrum of Betatron x-rays averaged over ten successive shots. As the x-ray beam has a pointing fluctuation of the order of the beam size, it can be regarded as an averaged spectrum over angles. The average also allows us to give



**Figure 3.** Spectra of Betatron x-rays obtained from photon counting, for laser shots 1 (red), 2 (green) and 3 (blue) corresponding to the electron spectra given in figure 2, and the best fit with a synchrotron distribution for each laser shot.



**Figure 4.** Spectrum of Betatron x-rays obtained from photon counting, averaged over ten shots (red line), and the best fit to a synchrotron distribution of critical energy  $E_c = \hbar\omega_c = 5.6 \text{ keV}$  (green line). We illustrate the precision over the critical energy determination by showing the synchrotron distribution corresponding to  $E_c = \hbar\omega_c = 5.6 \pm 1 \text{ keV}$  (green dashed lines).



a typical spectrum (since shot-to-shot fluctuations are important) and to improve the signal-to-noise ratio. A fit of the experimental measurement by a synchrotron distribution (of the type  $S(\omega/\omega_c)$  as defined above) is also shown. The best fit was obtained with a synchrotron distribution of critical energy  $E_c = \hbar\omega_c = 5.6$  keV. The measurement precision over the critical energy is  $\pm 1$  keV.

In conclusion, we have presented a single shot and large spectral range characterization of laser-produced Betatron radiation. In this experiment, the source produced  $3.6 \times 10^7$  and  $1.1 \times 10^7$  photons/0.1% bandwidth/sr/shot at 10 and 20 keV, respectively. The result shows unambiguously that the single-shot experimental spectra fit synchrotron distributions. The averaged spectrum has a best fit for  $E_c = 5.6 \pm 1$  keV. The high critical energy obtained in these experiments demonstrates the potential of this x-ray source for diffraction and imaging applications. It also shows the interest for the 100 TW scale laser system to go beyond the 10 Hz repetition rate in order to increase the x-ray source average brightness.

## Acknowledgments

We thank the ALLS technical team for their support, namely M O Bussière, J Maltais, C Morissette, L Pelletier, F Poitras, P L Renault and C Sirois. The ALLS facility has been funded by the Canadian Foundation for Innovation (CFI). This work was funded by NSERC, the Canada Research Chair program and Ministère de l'Éducation du Québec. We acknowledge support from Agence Nationale pour la Recherche through the COKER project ANR-06-BLAN-0123-01.

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